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ORIGINAL ARTICLE

Performance of small-scale aero-derivative industrial gas turbines derived from helicopter engines

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Simple-cycle;
Specific-fuel-consumption;
Performance assessment;
Helicopter engine

Abstract This paper considers comparative assessment of simple and advanced cycle small-scale aero-derivative industrial gas turbines derived from helicopter engines. More particularly, investigation was made of technical performance of the small-scale aero-derivative engine cycles based on existing and projected cycles for applications in industrial power generation, combined heat and power concept, rotating equipment driving, and/or allied processes. The investigation was done by carrying out preliminary design and performance simulation of a simple cycle (baseline) two-spool small-scale aero-derivative turboshaft engine model, and some advanced counterpart aero-derivative configurations. The advanced configurations consist of recuperated and intercooled/recuperated engine cycles of same nominal power rating of 1.567 MW. The baseline model was derived from the conversion of an existing helicopter engine model. In doing so, design point and off-design point performances of the engine models were established. In comparing their performances, it was observed that to a large extent, the advanced engine cycles showed superior performance in terms of thermal efficiency, and specific fuel consumption. In numerical terms, thermal efficiencies of recuperated engine cycle, and intercooled/recuperated engine cycles, over the simple cycle at DP increased by 13.5%, and 14.5% respectively, whereas specific fuel consumption of these cycles

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over simple cycle at DP decreased by 12.5%, and 13% respectively. This research relied on open access public literature for data.

1. Introduction

Guided by different power requirements and application scenarios, three categories of aero-derivative gas turbines are identified: (i) small-scale aero-derivatives, (ii) medium-scale aero-derivatives, and (iii) large-scale aero-derivatives. The small-scale aero-derivatives are thought of to emanate from the conversion of aero-engines of small capacity aircrafts such as helicopter engines to industrial configuration having low power rating up to about 4 MW. Power rating above this range up to about 50 MW could be termed medium-scale aero-derivatives, whereas above 50 MW define the class of large-scale aero-derivatives. The small-scale aero-derivative engines considered in this piece of work are those converted from helicopter gas turbine engines. In reference [1] the authors have dealt with the performances of simple and advanced cycle helicopter turboshaft gas turbines.

Turboshafts are gas turbine engines which provide power for rotary wing aircrafts, or helicopters. Turbo-shaft engines may be single-spool or multi-spool. The single-spool configurations are employed basically to minimize weight. This is particularly true for light weight helicopters [1,2]. Free power turbine configuration with a single spool or in some cases two spool gas generator characterize turbo-shaft engines. The turbo-shaft engine is designed so that the speed of the helicopter rotor is independent of the rotating speed of the gas generator [1,3].

Using heat exchangers (both recuperators and intercoolers) in an engine exhibits tremendous potential to cut fuel consumption and thereby reducing CO_2 emissions. It was explained that the recuperator utilises part of heat from the exhaust gas to raise the temperature of the air entering the combustor [4]. This method makes achievement of the same turbine entry temperature as in a conventional engine possible, but with the advantage of utilizing lesser fuel [4]. Besides, gas turbine user requirements have, over the years, necessitated technological advancement in engine performance, and comprehensive researches are being conducted to achieve this [1,5].

Technically, improvement of thermal efficiency for industrial and aero gas turbines is of paramount importance to the overall performance of the engines. Increase in thermal efficiency depends on certain factors including: Changes in some engine cycle parameters, such as overall pressure ratio (OPR), and turbine entry temperature (TET). Cutting-edge technology of engine components like methods of cooling, efficiencies of components, ducts pressure losses, and introduction of different overall thermodynamic cycle, for example, use of unconventional components like intercoolers and regenerators or recuperators [6,7]. More so, performance and economic viability of gas turbines are inseparable [1].

In this paper the conversion of helicopter gas turbine engines to aero-derivative industrial engines, and assessment of their technical performances are considered. The investigation undertook a comparative assessment of simple and advanced engine cycle options. The contribution of this work lies in the substantiation of the technical benefit of advanced engine cycles like ICR and recuperated cycles in small-scale aero-derivatives even as they could be derived from helicopter engines.

2. Method

2.1. Design point performance (DP)

The Design Point of a gas turbine could be defined as the very condition in the operating range of a gas turbine when the engine is running at the very mass flow, speed, and pressure ratio for which the components were designed [8]. In establishing the design point of the engine, pressure ratio and TET that results in an overall highest thermal efficiency are normally determined from preliminary cycle calculations. After this is done, other appropriate design parameters of the gas turbine system may be allotted. Then, detail design of different engine components can be done in order to provide the specified requirements of the complete system when operating at the DP. There are many requirements from a gas turbine engine. These may be referred to as design priorities, and always these requirements are in conflict. The design of the engine is greatly influenced by a set of these priorities depending on the engine application [1,6,9].

2.2. Off-design performance (OD)

Besides the DP performance of the gas turbine, it is mandatory to ascertain its general performance over the entire operating range of power output and speed. This is known as Off-Design (OD) performance [8]. Component characteristics as indicated by component maps of compressor, turbine, and combustor, are very useful in ascertaining off-design behaviour of the gas turbine system. At steady state operation of the engine, corresponding operating points on the component maps are matched and can be plotted on the compressor characteristic diagram to form an equilibrium running line [1].

Various performance plots of power output, specific fuel consumption (SFC), thrust, specific thrust or power, etc

Nomenclature

CN non-dimensional speed
CU Cranfield University
CW compression work (unit: kJ)
DP design-point
EC Eurocopter
EW expansion work (unit: kJ)
FPT free power turbine
FPTW free power turbine work
GT gas turbine
HP high pressure
HPC high pressure compressor
HPCW high pressure compressor work
HPT high pressure turbine
HPTW high pressure turbine work
ICR intercooled/recuperated
Inter intercooler
ISA international standard atmosphere
ISA Dev international standard atmosphere deviation
LP low pressure
LPC low pressure compressor
LPCW low pressure compressor work
LPT low pressure turbine
OD off-design point
OEM original equipment manufacturer
OPR overall pressure ratio
PR pressure ratio
RC recuperated cycle
SC simple cycle
SFC specific fuel consumption (unit: kg/(MW · s))
SLS sea level static
TERA techno-economic and environmental risk analysis
TET turbine entry temperature (unit: K)
TURBOMATCH gas turbine engine performance model code
USAF United State Air Force
c specific heat (unit: kJ/kg)
c_p specific heat at constant pressure (unit: kJ/kg)
h specific enthalpy (unit: kJ/kg)
P total pressure (unit: N/m^2)
q heat flow (unit: kW)
q_{in} heat flow in (unit: kW)
q_{out} heat flow out (unit: kW)
S entropy (unit: kJ/(kg · K))
T total temperature (unit: K)
Z surge margin parameter

Greek letters

ε heat exchanger effectiveness
η efficiency (unit: %)
η_{th} thermal efficiency (unit: %)
η_c compressor isentropic efficiency (unit: %)
η_T turbine isentropic efficiency (unit: %)
π pressure ratio at design point
π_{choke} pressure ratio at choke condition
π_{surge} pressure ratio at surge condition

Subscripts

p at constant pressure
th thermal
in inlet
out outlet
$regen$ regeneration
1,2,3,4,5,6,7,i engine components station numbers

could be made once the operating conditions of an engine have been determined. It is important to note that off-design performance is very much affected by factors such as ambient conditions of temperature and pressure, altitudes, flight speed (for aero engines), etc. The off-design performance analysis is normally achieved by the use of computer model simulations of engines [1,10].

2.3. TURBOMATCH

Engine components operating point matching to establish OD performance is normally a tedious and time consuming task since it is an iterative process. Computer based simulation is normally employed to accomplish the task. TURBOMATCH is an in-house gas turbine engine performance software developed and established at Cranfield University (CU). It is employed to simulate the DP and OD performances of a broad range of aero and industrial gas turbines. Simple single shaft engines, complex multi-spool engines, as well as novel cycle engine configurations can be modelled adequately using the scheme [1].

In the scheme, different engine components (intake, compressor, combustor, turbine, nozzle, etc) are represented by bricks (building blocks of the programme). These bricks are pre-programmed routines deployed to simulate, on a modular basis, the performance of the various engine components they represent. The cycle thermal efficiency, specific fuel consumption, power, or thrust of the engine, etc are essential performance output parameters that are obtained as desired results of the simulation. Besides these overall cycle results, individual component performance characteristics, and the working-fluid properties at various stations within the engine are also outputted [1,8,11–13].

2.4. Simple cycle turboshaft engine with free power turbine

In this paper, two-spool turboshaft engine with a free power turbine (FPT) was considered in which a low pressure compressor (LPC) and a high pressure compressor (HPC) are driven by the high pressure turbine (HPT). The schematic of this engine is shown in Figure 1.

The T-S diagram of the simple cycle is as shown in Figure 2 considering isentropic efficiencies of compressors and turbines. With the notations of Figure 1 and Figure 2, and applying steady flow energy equation, heat flow into the cycle in the combustion chamber (process 3-4) per unit air mass flow is given by Eq. (1).

$$q_{in} = h_4 - h_3 = c_{pi}(T_4 - T_3) \quad (1)$$

where c_{pi} is the specific heat capacity at constant pressure, which varies with temperature at the given engine component station *i*. *i* represents engine station numbers 1, 2, 3, 4, 5, 6 etc.

Heat rejected at constant pressure (process 6-1) in the exhaust is given by Eq. (2).

$$q_{out} = h_6 - h_1 = c_{pi}(T_6 - T_1) \quad (2)$$

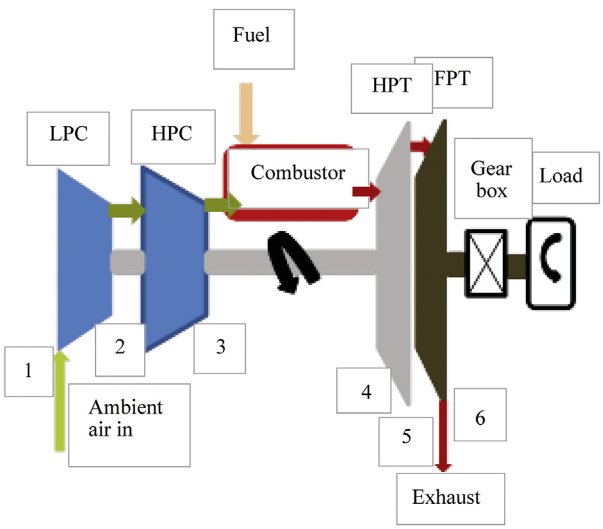

Figure 1 Schematics of simple cycle turbo shaft engine with free power turbine [1].

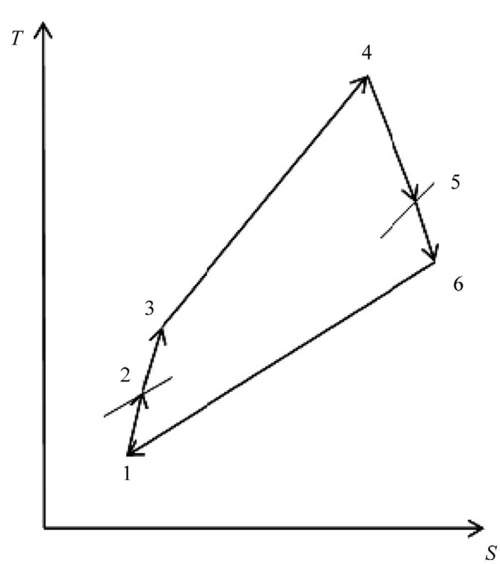

Figure 2 T-S diagram of actual simple cycle of the two-spool engine with free power turbine [1].

Eq. (3) gives the total compressor work (CW) (process 1-2-3) per unit air mass flow, where process 1-2 occur in the LPC and process 2-3 occur in the HPC.

$$CW = LPCW + HPCW = (h_2 - h_1) + (h_3 - h_2)$$
$$CW = c_{pi}[(T_2 - T_1) + (T_3 - T_2)] \quad (3)$$

High pressure turbine work (HPTW) (process 4-5) per unit air mass flow is defined by Eq. (4).

$$HPTW = h_4 - h_5 = c_{pi}(T_4 - T_5) \quad (4)$$

Free power turbine work (FPTW) (process 5-6) given by Eq. (5)

$$FPTW = h_5 - h_6 = c_{pi}(T_5 - T_6) \quad (5)$$

This implies that total expansion work (EW) is obtained as stated in Eq. (6)

$$EW = HPTW + FPTW$$
$$EW = c_{pi}[(T_4 - T_5) + (T_5 - T_6)] \quad (6)$$

The thermal efficiency is calculated using Eq. (7) [1] below.

$$\eta_{th} = \frac{useful\ work}{heat\ input} = \frac{EW - CW}{c_{pi}(T_4 - T_3)} \quad (7)$$

2.5. *Modifications to the simple cycle*

To increase the efficiencies of the simple-cycle, unconventional components are added to the cycle. These components include such like intercoolers, regenerators (recuperators), or reheaters. However, the initial and maintenance costs of the cycle may increase due to these additional components. The improvements in cycle performance brought about by these components can only be justified if the decrease in fuel costs offsets the increase in other costs. There is the general urge to reduce fuel consumption in gas turbine operation [14]. This is achieved by the introduction of these modifications to the simple cycle. The descriptions of these modifications are outlined below [1].

2.5.1. *Recuperated cycle*

The turboshaft engine in Section 2.4 with a recuperator is represented on the T-S diagram as shown in Figure 3. The recuperator or regenerator is a heat exchanger connected between the turbine exhaust and the compressor exit. The thermal efficiency of the cycle increases due to recuperation because the portion of heat in the exhaust gases that is supposedly wasted by flaring is now utilised to preheat the air at the exit to the compressor. This, in effect, reduces the heat gain from burning fuel, and hence, decreases fuel consumption for same power output. However, if the compressor outlet temperature is equal or higher than the turbine exhaust temperature, the use of a regenerator is not recommended. Else, there will be a reversal of heat flow to the exhaust gases, causing the efficiency to decrease.

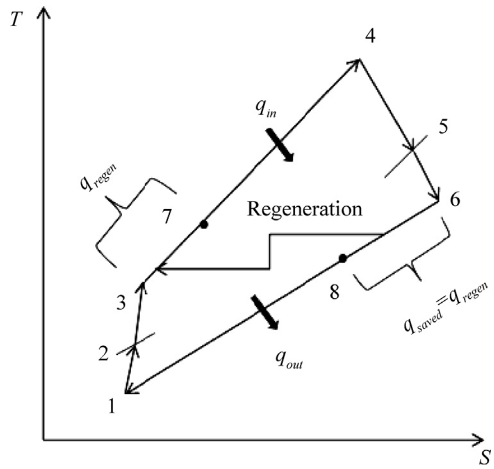

Figure 3 T-S diagram of actual cycle with a regenerator [1].

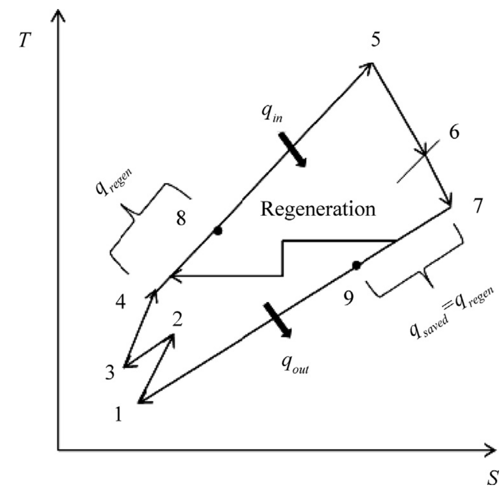

Figure 4 T-S diagram of actual intercooled/recuperated cycle [1].

Very high pressure ratios in gas-turbine engines could cause this adverse situation [1].

Referring to the cycle in Figure 3, T_6 is the maximum temperature that can occur within the recuperator which is the temperature of the exhaust gases entering the recuperator and leaving the turbine. Air in the regenerator (recuperator) can only be preheated to a temperature below T_6, and air will normally exit the regenerator at T_7, a lower temperature [1,15]

The heat input per unit air mass flow here is given by Eq. (8).

$$q_{in} = h_4 - h_7 = c_{pi}(T_4 - T_7) \tag{8}$$

Eq. (9) [1,15] calculates the thermal efficiency in this case making reference to Eq. (3) and Eq. (6).

$$\eta_{th} = \frac{useful\ work}{heat\ input} = \frac{EW - CW}{c_{pi}(T_4 - T_7)} \tag{9}$$

2.5.2. Intercooled/recuperated cycle

Incorporating an intercooler between the LPC and HPC of the recuperated engine in Section 2.5.1 such that air leaving the LPC is cooled before entering the HPC, results in an intercooled/recuperated cycle. Intercooling reduces the total compressor work, thereby, increasing useful work output, turbine work remaining the same [6]. Also, intercooling will increase the specific work of the cycle, increase heat input from combustor, and thus fuel consumption will rise [16]. However, this intercooler effect of reducing thermal efficiency is compensated by recuperation effect in ICR. The T-S diagram for the cycle with both intercooling and recuperation is as shown in Figure 4, where process 2-3 is intercooling.

Using the station numbering and notations in the T-S diagram of Figure 4, intercooler effectiveness is given by Eq. (10) [1,15] below.

$$\varepsilon_{\text{int}\ er} = \frac{T_2 - T_3}{T_2 - T_1} \tag{10}$$

Here compressor work is given by Eq. (11), and Eq. (12) gives the expansion work.

$$CW = LPCW + HPCW = (h_2 - h_1) + (h_4 - h_3)$$
$$CW = c_{pi}[(T_2 - T_1) + (T_4 - T_3)] \tag{11}$$

$$EW = c_{pi}[(T_5 - T_6) + (T_6 - T_7)] \tag{12}$$

Eq. (13) calculates the thermal efficiency in this case with reference to Eq. (11) and Eq. (12).

$$\eta_{th} = \frac{useful\ work}{heat\ input} = \frac{EW - CW}{c_{pi}(T_5 - T_8)} \tag{13}$$

TURBOMATCH code is capable of computing engine performance parameters using thermodynamic relations and models, considering variations of properties of working fluid at different conditions of pressure and temperature [11–13].

3. Simulation results

Preliminary design of the engine model is the starting point for assessing the performance of any gas turbine engine. The nature of application and the shaft power requirement are important factors to be considered when making choice of engine model sizing [1].

3.1. Base-line engine core

Considering the envisaged small-scale industrial application and the corresponding range of power rating (about 1-2 MW), coupled with availability of data, the choice of engine core for the preliminary engine model was made. This core is inspired by Makila 2 A core, a Turbomeca helicopter turbo-shaft engine. This engine was specially developed to power 11-ton twins, like Eurocopter EC225 and EC725 [18]. The Makila 2 A is a two-spool turbo-shaft

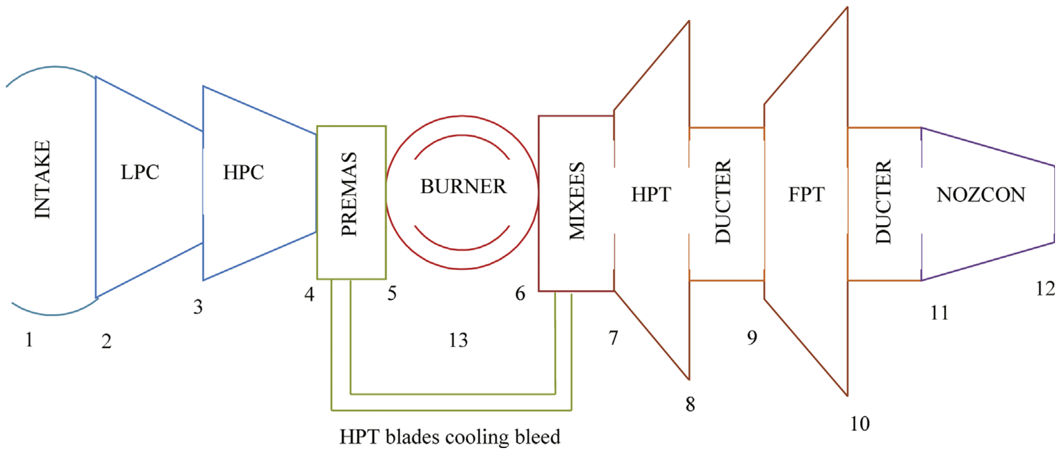

Figure 5 Simple cycle two-spool turboshaft engine with free power turbine in TURBOMATCH bricks.

engine with a free power turbine which is capable of delivering 1567 kW (2101 shp) at take-off ISA SLS. Its power output shaft speed is 23,000 rev/min; air mass flow is 5.7 kg/s, and pressure ratio of 11:1 [1,18–20]. This engine is converted to aero-derivative industrial engines by effecting some key changes to the engine core parameters. In what follows these changes are detailed, firstly in converting the helicopter engine to a baseline simple cycle aero-derivative industrial engine. Thereafter the resulting simple cycle (baseline) aero-derivative engine is modified by incorporating components such as recuperator, and intercooler to form a recuperated (RC) cycle, and an intercooled/recuperated (ICR) cycle, all having the same nominal power rating.

3.2. *Simple cycle two-spool aero-derivative engine design point performance simulation*

It should be understood that the design point of the inspiring engine core is proprietary information of the original equipment manufacturer (OEM), and as such, the design point is reasonably chosen by the engineering judgment. This is because some key defining parameters of the DP like the turbine entry temperature (TET), etc. are not usually disclosed by the OEM [1,21]. Based on this fact, and due to availability of data, international standard atmosphere (ISA), and sea level static (SLS) was chosen as the design point with the adoption of U.S.A.F. standard for pressure recovery at intake for the parent engine – the helicopter engine. Simulation of the helicopter engine has been carried out by same authors in their paper of reference [1].

In order to carry out computation of the aero-derivative engine performance, the engine components were modeled in Turbomatch bricks as shown in Figure 5. The simple cycle aero-derivative baseline engine components in TURBOMATCH bricks are arranged samely as that of the helicopter turboshaft engine. However, as typical of conversion to aero-derivative industrial gas turbines, the following changes were made to the engine and component parameters. Pressure recovery at the intake was set to 0.9951, with compressor surge margin increased by 0.05. Compressor and turbine isentropic efficiencies were reduced. The corrected rotational speeds of the compressors were reduced to 0.8, and the inlet mass flow and HP turbine cooling bleed reduced. The turbine entry temperature and component efficiencies were assumed. Both compressors are driven by the HP turbine. A combustion chamber pressure loss of 5% of the HPC delivery pressure was allowed. Maintaining the TET at 1500 K, and ISA SLS as the design point, the engine was simulated in TURBOMATCH codes and the DP performance result generated. The design parameters of the parent engine and the derivative are presented in Table 1 below and a summary of the performance of the aero-derivative engine is shown in Table 3.

Table 1 Design parameters of the simple cycle engine.

Design parameter	Value for parent helicopter engine	Value for aero-derivative engine
Power rating (Free power turbine)/kW	1567	1567
Compressor isentropic efficiencies	0.79	0.78
Surge margin parameter	0.85	0.80
Overall pressure ratio	11.25	11.25
LP compressor pressure ratio	2.5	2.5
HP compressor pressure ratio	4.5	4.5
Turbine entry temperature/K	1500	1500
Inlet air mass flow/kg	5.7	5.53
Combustor efficiency	0.99	0.99
HP turbine isentropic efficiency	0.88	0.87
Power turbine isentropic efficiency	0.89	0.88
Bleed for HP turbine inlet blade cooling/%	10	9

The surge margin parameter in Table 1 is the factor that limits the compressor operating point from coinciding on the surge line in order to prevent the compressor from surge. In TURBOMATCH code, surge margin parameter lies between 1.00 and zero. Depending on pressure ratios, in TURBOMATCH code, as surge margin tends to the value of 1.00, operating point approaches surge condition and as it tends to zero, operating point approaches choke condition. The surge margin of 0.85 allotted in the parent helicopter engine design was the default value in TURBOMATCH and means that the operating point is kept literally at a safe distance from the surge line [1]. In the case of the aero-derivative engine, the surge margin parameter is reduced to 0.80. Surge margin parameter Z is defined by Eq. (14).

$$Z = \frac{(\pi - \pi_{choke})}{(\pi_{surge} - \pi_{choke})} \tag{14}$$

where, π = pressure ratio at design point, π_{surge} = pressure ratio at surge condition, and π_{choke} = pressure ratio at choke condition [1,11].

The simulation was run in TURBOMATCH, and the output file gave the performance results as shown in Table 3. The quantified T-S diagram of the simple cycle analysis is presented in Figure 6, noting that temperature variation is the paramount parameter.

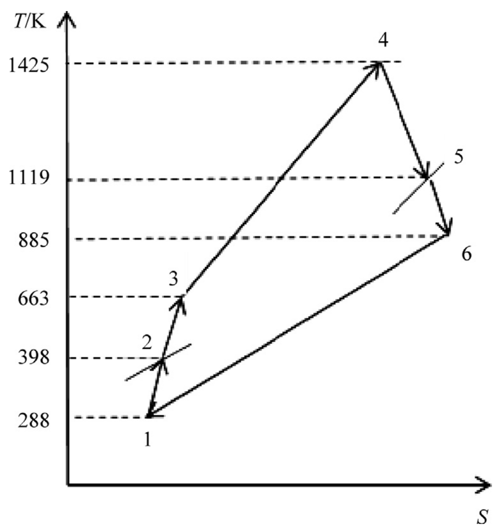

Figure 6 T-S diagram of DP analysis of the simple cycle.

Table 2 Additional design parameters of the recuperated cycle engine.

Design parameter	Value
Recuperator effectiveness	55%
Cold side pressure loss	3%
Hot side pressure loss	3%

3.3. DP simulation recuperated aero-derivative engine

A recuperator was added after the LP power turbine of the simple cycle aero-derivative engine described in Section 3.2, while retaining component efficiencies, TET, OPR, and inlet mass flow as stated in Table 1. The additional design parameters of the recuperated cycle are as shown in Table 2. This engine was simulated for DP performance and a summary of the result is shown in Table 3.

A bleed of about 7.5% of inlet air flow for the HP turbine inlet blades cooling, and a mass flow leakage of 0.02 kg for the recuperator, were allowed. ISA SLS was maintained as design point and DP cycle analysis is indicated in the T-S diagram of Figure 7.

3.4. Intercooled/recuperated aero-derivative engine DP simulation

The core engine parameters of the recuperated aero-derivative were retained while an intercooler was incorporated between the LPC and HPC. This is aimed at lowering the temperature of the air entering the HP compressor in order to reduce the work done by the HP compressor, and consequently, the overall compression work is reduced, and as such, cycle efficiency will improve. A bleed of 20% of

Table 3 Summary of DP performance results of the aero-derivative engines.

Performance parameter	Value at DP of simulated aero-derivative engines		
	Simple cycle (SC) (baseline)	Recuperated (RC)	ICR
Power turbine rating/kW	1567	1567	1567
Inlet mass flow/(kg/s)	5.53	5.53	5.53
Exhaust mass flow/(kg/s)	5.66	5.638	5.64
Fuel flow/(kg/s)	0.125	0.108	0.107
Exhaust gas temperature/K	890	900	826
Overall pressure ratio	11.25:1	11.25:1	11.25:1
Thermal efficiency	0.296	0.336	0.339
LPC work/kW	614	614	614
HPC work/kW	1517	1517	1146
HPT power/kW	2131	2131	1760
variation in HPT power of advanced cycles over that of SC/%	0	0	−17.41

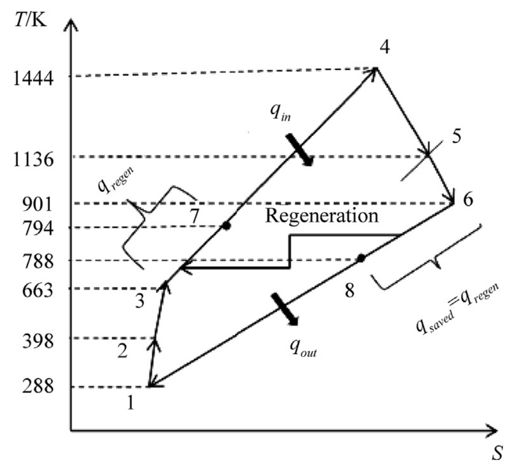

Figure 7 DP analysis of the recuperated cycle on T-S diagram.

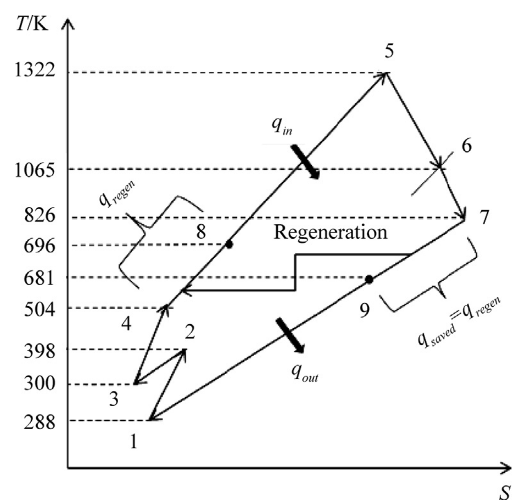

Figure 8 T-S diagram of DP analysis of ICR cycle.

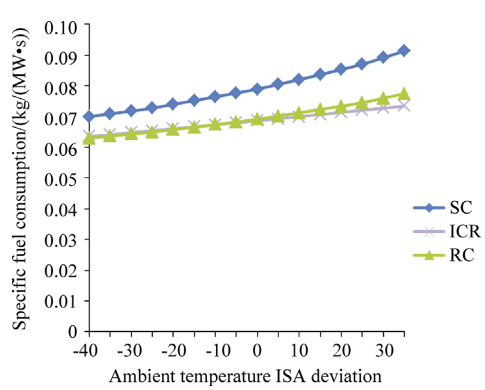

Figure 9 Variation of SFC with ambient temperature at ISA SLS.

the inlet air mass flow was allowed for HP turbine inlet blade cooling. The air leaving the LP compressor was cooled to a temperature of 300 °C which results from an intercooler effectiveness of 89%, and a pressure loss of 4% of LP compressor delivery pressure.

Maintaining ISA SLS as design point the intercooled/recuperated engine was simulated, and the DP performance result is as indicated in Table 3. Its T-S diagram is presented in Figure 8.

The values of LPC work and HPC work in Table 3 above indicate the variation in compressor work due to intercooled/recuperation. The power produced by the HPT changes accordingly to the sum of the compressor powers being the only turbine that drives both compressors. At DP the FPT output was assumed fixed for all four cycles and so is not affected by the variation in compressor work because it is not driving any of the compressors. The rational here was to compare performances of cycles with the same nominal power rating in terms of thermal efficiency and fuel consumption. Recuperation alone has no noticeable effect on compressor work. However, all the advanced configurations reduced the fuel flow which eventually reduced heat energy input in combustor and hence increased thermal efficiency.

3.5. Off-design performance of the engines

By the use of component maps in TURBOMATCH codes, the off-design performances of all the aero-derivative engine versions were simulated and the variations of some key output parameters were as plotted in Figure 9 to Figure 12. The discussion of these results is presented in Section 4. As described in Section 2.2, gas turbine engines normally do not operate at the DP in practice due to the effects of conditions such as changing ambient temperature, altitude, turbine entry temperature, among others.

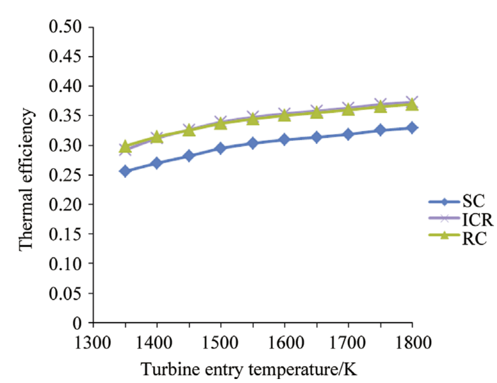

Figure 10 Variation of thermal efficiency with TET at ISA SLS.

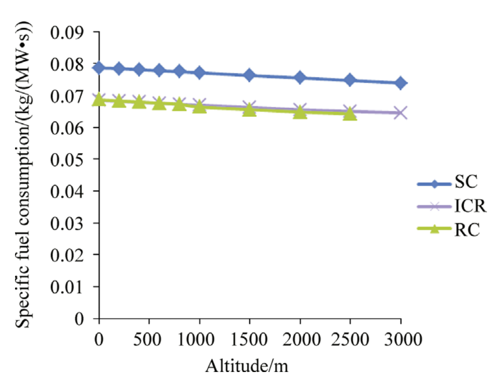

Figure 11 Effect of altitude on SFC.

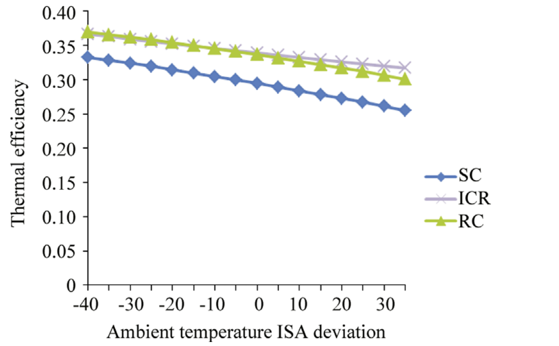

Figure 12 Effect of ambient temperature on thermal efficiency.

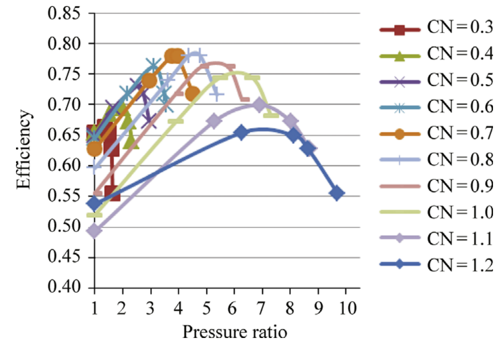

Figure 15 HP compressor map of efficiency versus pressure ratio.

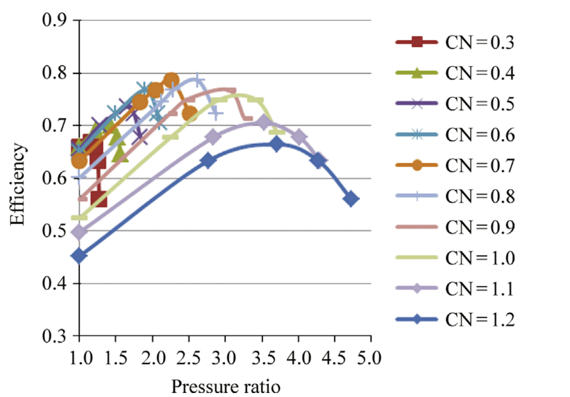

Figure 13 LP compressor map of efficiency versus pressure ratio.

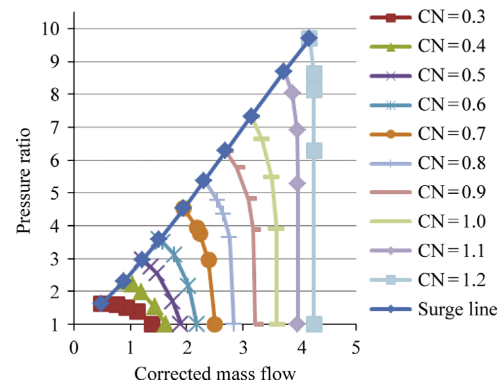

Figure 16 HP compressor map of corrected mass flow versus pressure ratio.

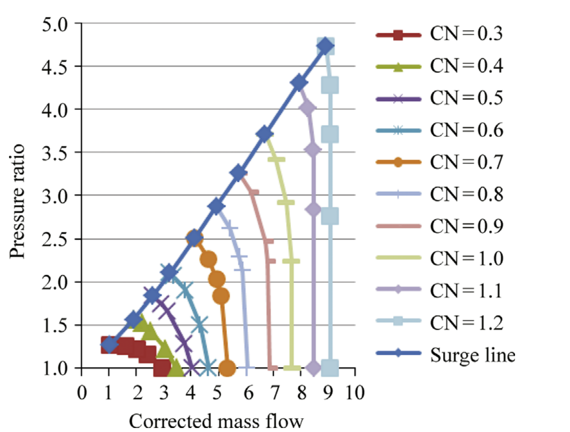

Figure 14 LP compressor map of pressure ratio against corrected mass flow.

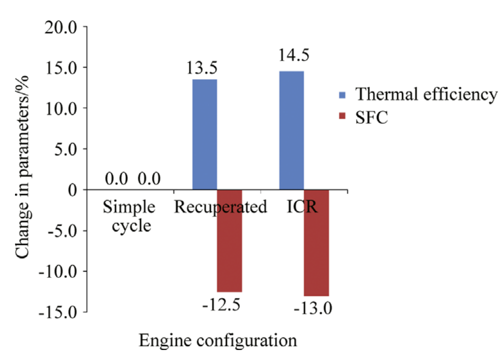

Figure 17 Percentage changes in performance parameters of advanced cycles over simple cycle.

The compressor maps are the most important component maps when it pertains analysing the off-design performance of an engine [12]. Figure 13 to Figure 16 shows the scaled compressor maps applied in TURBOMATCH to implement the off-design performances of the engine cycles, where CN refers to non-dimensional speed.

4. Results discussion

From the simulation results shown in Table 3 and plots of Figure 9 to Figure 12 it could be observed that both the recuperated and intercooled/recuperated aero-derivative engines exhibit higher thermal efficiency compared to the simple cycle – baseline engine at both DP and off-design point. The percentage increase in thermal efficiency of these advanced cycle engines over the traditional simple cycle engine especially at DP are shown in Figure 17 below. More so, specific fuel consumption is less in the advanced cycle engines than the simple cycle. This is made possible because the recuperator increases the temperature of air entering the combustor to reduce the quantity of heat flow required from burning fuel by heat-exchange action with stream of exhaust gas. The ICR cycle combines both advantages of recuperator heat-exchange discussed above and intercooling to achieve increased thermal efficiency; in which case, intercooling lowers the HPC work.

The negative sign on the SFC in Figure 17 above indicates percentage reduction in SFC of advanced cycles over simple cycle – baseline engine.

However, it is important to note that though the thermal efficiency is improved by using the advanced cycles, the incorporation of intercoolers and recuperators would make the engine more complex. This would increase the capital and maintenance cost actually, but cost of fuel would reduce due to reduction in fuel consumption.

5. Conclusion

Performance simulation of a simple cycle (baseline) two-spool small-scale aero-derivative industrial gas turbine derived from helicopter engine, and some advanced cycle configurations was implemented with the aid of appropriate software based on gas turbine theory. Such advanced cycles include recuperated, and ICR, engine cycles. In doing so, design and off - design point performances of the engine models were established. The results of performance parameters for the simulated baseline engine compares favourably with those obtained in the public domain.

It is observed that to a large extent, the advanced engine cycles exhibit better performances in terms of thermal efficiency and specific fuel consumption, than the traditional simple cycle engine. The percentage increases in thermal efficiencies of recuperated engine cycle, and intercooled/recuperated engine cycle, over the simple cycle at DP are 13.5%, and 14.5% respectively, whereas percentage reduction in specific fuel consumption of these cycles over simple cycle at DP are 12.5%, and 13% respectively.

These results compare favorably with values obtained in public domain literature. For instance, it was reported that the 1.4 MW intercooled/recuperated Heron-1 turbo-shaft gas turbine manufactured by EECT of the Netherland, exhibits thermal efficiency of 42.9% while a simple cycle gas turbine of same power range has thermal efficiency of about 26%–34%. This represents a thermal efficiency increase of about 26.2% at the minimum [22]. More so, percentage increases were reported of thermal efficiencies of recuperated engine cycle, and intercooled/recuperated engine cycle, over simple cycle of a turboshaft engine at DP as 20.6%, and 24.2% respectively, whereas percentage reduction in specific fuel consumption of these cycles over simple cycle at DP as 17.3%, and 21.1% respectively [1].

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References

[1] B. Nkoi, P. Pilidis, T. Nikolaidis, Performance assessment of simple and modified cycle turboshaft gas turbines, Propulsion and Power Research 2 (2) (2013) 96–106, http://dx.doi.org/10.1016/j.jppr.2013.04.009.

[2] P.P. Walsh, P. Fletcher, Gas Turbine Performance, Second ed., Blackwell Publishing, 2004, p. 38.

[3] B. Bellis, Turbo-shaft engines, about.com guide, ⟨http://inventors.about.com/od/jstartinventions/ss/jet_engine_4.htm⟩ [cited 28 June 2012].

[4] D. Dilba, Pioneering new core engine technologies. MTU Aero Engines, MTU Aero Engines Holding AG., ⟨http://www.mtu.de/en/takeoff/report/archive_old/2_2010/210_newac/index.html⟩ [cited 6 September 2012].

[5] M.D. Paramour, M.J. Sapsard, Future technology and requirements for helicopter Engines, in: W.A. Stewart (Ed.), NATO-AGARD conference on helicopter propulsion systems - AGARD-CP-302, Toulouse, France, 11–14 May 1981, pp. 4-1–4-6.

[6] R.T.C. Hartman, Gas Turbine Engineering: Application, Cycles, Characteristics, The MacMillan Press Ltd, London and Basingstroke, 1981, pp. 34–52.

[7] R.K. Bhargava, M. Bianchi, S. Campanari, A. De Pascale, G. Negri di Montenegro, A. Peretto, A parametric thermodynamic evaluation of high performance gas turbine based power cycles, Journal of Engineering for Gas Turbines and Power 132 (2) (2010) (022001.1-022001.14).

[8] J. Kurzke, Gasturb 8.0 user's manual, a program to calculate design and off-design performance of gas turbines, ⟨http://www.gasturb.de⟩ [cited 06 January 2012].

[9] Y.G. Li, P. Pilidis, M.A. Newby, An adaptation approach for gas turbine design-point performance simulation, Journal of Engineering for Gas Turbines and Power 128 (4) (2006) 789–795.

[10] Q.Z. Al-Hamdan, M.S.Y. Ebaid, Modeling and simulation of a gas turbine engine for power generation, Journal of Engineering for Gas Turbines and Power 128 (2) (2006) 302.

[11] J.R. Palmer, V. Pachidis, The TURBOMATCH scheme for aero/industrial gas turbine engine design point/off design performance calculation, Dissertation, School of Mechanical Engineering, Cranfield University, United Kingdom, 1983.

[12] W.L. MacMillan, Development of a modular-type computer program for the calculation of gas turbine off-design performance, PhD Dissertation, School of Engineering, Cranfield University, United Kingdom, 1974.

[13] L. Galla, V. Volpe, M. Salussolia, V. Pachidis, A. Jackson, Thermodynamic gas model effect on gas turbine performance simulations, Journal of Propulsion and Power 28 (4) (2012) 719–727.

[14] D. Lane, Brayton cycle: the ideal cycle for gas turbine engines, ⟨web.me.unr.edu/me372/Spring2001/Brayton%20Cycle.pdf⟩ [cited 19 June 2012].

[15] H.I.H. Saravanamutoo, G.F.C. Rogers, H. Cohen, P.V. Straznicky, Gas Turbine Theory, Sixth ed., Pearson Education Limited, 2009, pp. 1–3.

[16] T.K. Ibrahim, M.M. Rahman, A.N. Abd Alla, Study on the effective parameter of gas turbine model with intercooled compression process, Scientific Research and Essays 5 (23) (2010), ⟨http://www.academicjournals.org/SRE⟩ [cited 15 March 2012].

[17] P.A. Bromnick, R.J. Pearson, D.E. Winterbone, Intercooler model for unsteady flows in engine manifolds, in: Proceedings of the IMechE, part D, Journal of Automobile Engineering 212 (2) (1998) 119-132, ⟨http://pid.sagepub.com/content/212/2/119⟩ [cited 12 March 2012].

[18] Makila, Safran Turbomeca, ⟨http://www.turbomeca.com⟩ [cited 05 January 2012].

[19] Aero-engines: Turboshaft engines, in: Jane's All the World's Aircraft, Jane's Information Group, London, 2011, p. 939.

[20] Makila, Turbomeca – Aero-engines, France, Aero-Engines, issue 29, 2011, pp. 154-156, ⟨http://Jae.janes.com⟩ [cited 10 January 2012].

[21] E. Andreadis, Upgrade evaluation of a military turbofan engine, Dissertation, Power and Propulsion Department, School of Engineering, Cranfield University, United Kingdom, 2009.

[22] R. Farmer, Intercooled recuperated 1400 kW genset has an 8000-Btu heat rate, Gas Turbine World, EECT B.V., The Netherland, March-April 2002, ⟨http://www.eect.nl⟩ [cited 10 October 2012].